A Robust Power Decoupler and Maximum Power Point Tracker Topology for a Grid-Connected Photovoltaic System

S. Ali Khajehoddin *,§, Alireza Bakhshai*, Praveen Jain†, and Josef Drobnik†
*Energy and Power Electronics Applied Research Laboratory (ePEARL), Queen’s University, Canada
† Freescale semiconductor Inc., 2100 E Elliot St., Tempe AZ 85284
§Email: khajeddin@ieee.org

Abstract—The exponential growth in the number of Photovoltaic (PV) system installations verifies that solar power technology has become one of the promising energy resources. This paper introduces new control scheme and converter topology for low to medium power PV applications. Proposed topology provides independent MPPT and power decoupling without the use of bulky electrolytic capacitors. The grid-connected output stage is a current source inverter with a modified modulation strategy to inject a low harmonic current into the grid at unity power factor. Simulation results are presented to show the effectiveness of the proposed method in terms of MPPT, power decoupling and power injection into the grid at a high quality.

I. INTRODUCTION

The solar energy received in one day is equivalent to more than ten times the annual energy consumption of everyone on earth. This revelation along with the worldwide trend of green energy, has led to an exponential growth of the number of Photovoltaic (PV) system installations [1]. At this moment, the major obstacle of wide PV system commercialization is the high initial investment cost that stems from the strict grid connection standards and high expectations from the PV system [2], [3]. The grid-connected PV system consists of two parts: PV arrays that convert irradiation to electrical energy, and the converter that feeds the energy into the grid. To keep overall output power per unit cost low, the grid-connected converters should be able to extract the maximum available power from the PV arrays. Since the PV array characteristic is highly nonlinear, maximum power point tracking (MPPT) of the PV arrays becomes rather challenging. The MPPT systems usually consists of two parts: an MPP tracker hardware, and an algorithm. The MPP tracker alters the input resistance of the converter seen from the output terminal of the PV cells that results in a change of the operating point. MPPT algorithms [4] calculate the best operating point available with the current irradiation and temperature of the PV cells and provides the reference point for the MPP tracker hardware. This paper provides a new topology for the MPP tracker circuit.

Another MPP tracker task is to decouple the output power pulsation from the input power generation. This is specifically a troublesome issue in single-phase grid-connected systems, where the instantaneous output power oscillates at twice the grid frequency. This results in a deviation from the optimum operating point [2]. This problem is usually resolved by a big electrolytic capacitor in the range of mF at the PV terminals, which in turn decreases the lifetime and increases the volume, weight and cost of the converter. To avoid the electrolytic capacitor, authors in [5], [6] proposed auxiliary circuits which draw constant current from the input and generate a high DC voltage at the middle stage to supply the pulsation required at the output. However, such solutions are for low power applications and exhibit low efficiency due to high voltage ratings, extra switching circuit, and are complex in hardware and control system which make the overall system expensive.

This paper introduces a new hardware configuration and a novel control strategy which uses a minimum number of components with optimized values to decouple the output power pulsations from input and to extract MPP. This circuit specifically avoid the usage of electrolytic capacitors, which is a major factor in limiting the circuit life time. A unique feature of the proposed topology in this paper is that the MPP tracker is not limited to low power applications. Simulation results show a good robustness and decoupling performance for medium power systems such as residential applications. The proposed converter configuration is a buck-boost current source inverter and thus the output voltage can be greater or smaller than the input PV module voltage level that provides a wide range of input voltage. Unlike the voltage source topologies, the proposed converter feeds the desired current into the grid using a modified PWM technique. The tracking capabilities and system responses for different temperature, irradiation and voltage levels are investigated through simulations that verify the theoretical concepts.

II. MAXIMUM POWER POINT TRACKER CIRCUIT DESIGN AND OPERATION

Fig. 1(a) illustrates the schematic diagram of the power circuit of the proposed MPP tracker and its control strategy. Although the power circuit resembles the topology of a buck converter, the proposed MPP tracker utilizes the main switch to regulate the input capacitor voltage. Controlling the input voltage enables the converter to displace the output power pulsation from input terminal through the control, and not as traditionally done by bulky input capacitors. Therefore, this topology requires a small and optimized input capacitor. It is important to note that substantial removal of the input voltage
Fig. 1. (a) Maximum Power Point Tracker control circuit. (b) PV module current, voltage and power waveforms.

oscillations stabilizes the input operating point resulting in a high efficiency with much smaller capacitors. In other words, this topology with its control and any MPP tracking algorithm [4] can always absorb the maximum power available from the PV cells independent from the output voltage and current. This power is delivered to the next stage and as it will be explained later, the output current and voltage of this stage are controlled and induced by the next stage. Fig. 1(b) illustrates one snap shot from the input voltage, current and power waveforms. It is clear that the MPP is tracked since in both rise time and fall time of the input capacitor the PV output power has an extremum.

The input capacitor voltage control can be briefly explained as follows. The capacitor voltage is maintained between two upper and lower levels. The upper level, $V_{pu}^{ref}$, is obtained from the MPPT algorithm. The lower level is calculated in such a way that under worst conditions, i.e. MPP, the switching frequency and the voltage ripple do not exceed a certain values. When the input capacitor voltage exceeds the upper level, the main switch turns on, and the capacitor is discharged. The switch remains on until its voltage hits the lower limit where it is turned off.

To limit the switching frequency, the lower limit is not a constant value and is a function of the desired frequency $f^d$ and the PV current level. The lower limit can be found as follows:

$$\Delta Q = C \Delta V_{pv} = i_{pv} t_{off} \Rightarrow \Delta V_{pv} = \frac{i_{pv}}{2C f^d} \quad (1)$$

For $C_1 = 20 \mu F, f^d = 20 K H z, i_{pv}^{max} = 4 A$, the PV voltage variation is $\Delta V_{pv} = 5 V$. It is clear from (1) that there is a trade off between the switching frequency and the capacitor value to obtain a desired PV voltage variation. Calculations show that to reach 98% utilization ratio, which is an indication of the loss due to deviation from the MPP, the voltage ripple should be less than $\Delta V_{pv} = %8.5V_{pv}^{MPP}$ [2]. The proposed control scheme satisfies this requirement because according to (1), when the irradiation level decreases (decrease of $i_{pv}$), the $\Delta V_{pv}$ also decreases which will guarantee the aforementioned condition for all conditions, if in the design procedure $V_{pv}^{MPP}$ was chosen to be the optimum voltage of the PV cell at the lowest operating temperature.

III. CURRENT SOURCE INVERTER DESIGN AND PRINCIPLE OF OPERATION

Fig. 2(a) demonstrates the power circuit diagram of the proposed inverter. The power circuit consists of two stages; the first stage is the MPP tracker circuit discussed in Section II and the second stage is a grid-connected current source inverter. $C_f$ and $L_f$ form a low pass filter to eliminate the output current high frequency components. Since the current supplied by the MPP tracker stage is not a constant dc source, the PWM technique must be modified. To do this, first the inductor current is formulated. Then, the reference signal to the PWM modulator is modified so that it regulates and controls the dc component of the inductor current, $i_L$, and prevents the double frequency harmonic component of $i_L$ from appearing in the output ac current.

A. Inductor DC Current Regulation

Assume that the converter is lossless ($P_{in} = P_{o}^{avg}$) and the output filter energy storage is negligible. Therefore, the only energy storage component is $L_B$. As discussed in Section II, the MPP tracker circuit will extract constant power from the PV modules. Assuming that the inverter generates a current in phase with the grid voltage, the output power can be derived as follows:

$$i_o(t) = I_o \sin(\omega t), v_o(t) = V_o \sin(\omega t) \Rightarrow$$

$$p_o(t) = \frac{1}{2} V_o I_o (1 - \cos(2\omega t)) \Rightarrow$$

$$P_{in} = P_{o}^{avg} = \frac{1}{2\pi} \int_{0}^{2\pi} p_o(t) dt = \frac{1}{2} V_o I_o \quad (2)$$

At $t = \pm \frac{\pi}{4}$, we have $p_o(t) = P_{in}$, and if $t \in (\pm \frac{\pi}{4}, \pm \frac{3\pi}{4})$, the input power will be greater than the output power. Therefore, for this period of time the inductor $L_B$ will be charged from $I_{Lmin}$ to $I_{Lmax}$.

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The following inequality have to be satisfied:

\[ \frac{1}{2} L I_{L,\text{max}}^2 - \frac{1}{2} L I_{L,\text{min}}^2 = \int T \left( P_{\text{in}} - p_o(t) \right) dt = \frac{P_{\text{in}}}{\omega} \]

\[ \Rightarrow \Delta I_L = \frac{P_{\text{in}}}{2\omega L T} I_L = I_{L,\text{min}} + I_{L,\text{max}} / 2 \]

Using the same procedure the inductor current can be derived as follows:

\[ i_L(t) = \sqrt{I_L + \frac{1}{2\omega L} V_o I_o \sin 2\omega t} \]

By reducing the modulation index the output current will be temporarily reduced. Consequently, the output power decreases and the difference energy will be stored in the inductor which will increase its dc value. As a result the output current will be increased up to the point that the average injected power equals the input power. To reduce the conduction losses, the inductor current can be simply minimized by the modulation index. Equations (4) and (5) show that the oscillation of the inductor current depends on the input power, the inductor value, and the inductor current. Thus, as the inductor current reduces, \( \Delta I_L \) increases and results in a discontinuous mode of operation. To avoid this mode of operation, the following inequality have to be satisfied:

\[ I_{L,\text{dc}} - \Delta I_L \geq I_o = \frac{2P_{\text{in}}}{V_o} \Rightarrow I_{L,\text{dc}} \geq \frac{P_{\text{in}}}{V_o} + \sqrt{\frac{P_{\text{in}}^2}{V_o^2} + \frac{P_{\text{in}}}{2\omega L}} \]

Since the minimum possible inductor current is desired, as shown in Fig. 2(b), the equality is used in the controller loop to generate a reference signal for the inductor dc current. To form the feedback loop, first the dc inductor value is measured and then the error signal is fed into a PI controller. The output of the PI controller adjusts the amplitude of the output current reference signal.

### B. Harmonic Cancelation Method

As shown in (5), the inductor current oscillates around a dc value at twice the grid frequency. The PWM technique assumes a constant dc input current and thus, any harmonic of the input source will be reflected to the modulated output current. This problem can be avoided by introducing a compensation factor as shown in Fig. 2(b). When the oscillating inductor current increases, the compensator decreases the modulation index proportionally. As a result, an increase in the inductor current value is compensated by a reduction in the modulation pulse width and vice versa. This type of compensation omits the oscillation because the energy transfer to the output will be equivalent to the case where the inductor current was a constant dc with no oscillation. The simulation results show that the output current has been fully compensated and contains no harmonic component at twice the grid frequency.

### IV. Simulation Results

To demonstrate the impact of the irradiance level and input voltage level on the performance of the system, a simulation is setup according to Table I, and the results are shown in Fig. 3. The voltage waveforms are scaled down by %50 to show the current waveform more clearly. The system is initially started at %10 of the full irradiation level. At t=0.12 (Sec) full irradiation is applied and the system response is obtained. At t=0.2 (Sec) the temperature of the cells are increased so that the output voltage of the pv cells are decreased from...
150V to 80V, which is less than the grid voltage. It can be seen that after any change, the controller takes a few cycles to stabilize the output current. However, the maximum input power extraction is almost instantaneous.

V. CONCLUSION

A grid connected converter topology for PV systems using a string configuration is proposed. The principle of operation of the two stage grid-connected photovoltaic converter and related control strategies are discussed in details. It is shown that the first stage performs both Maximum Power Point Tracking and the decoupling tasks with a minimum number of components with optimized values. The second stage is a current source inverter employing a modified modulation technique that injects a current with low total harmonic distortion into the grid. Simulation results are provided to demonstrate the performance of the converter and to verify the validity of the proposed topology.

REFERENCES


